

A Survey of Ground Operations Tools Developed to Simulate the Pointing Of Space Telescopes and the Design for WISE

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ABSTRACT

WISE, the Wide Field Infrared Survey Explorer, is scheduled for launch in June 2010. The mission operations system for WISE requires a software modeling tool to help plan, integrate and simulate all spacecraft pointing and verify that no attitude constraints are violated. In the course of developing the requirements for this tool, an investigation was conducted into the design of similar tools for other space-based telescopes. This paper summarizes the ground software and processes used to plan and validate pointing for a selection of space telescopes; with this information as background, the design for WISE is presented.

1. INTRODUCTION

WISE is an earth-orbiting spacecraft carrying an infrared telescope which will be cooled by means of a cryostat filled with solid hydrogen. The purpose of the mission is to conduct an all-sky survey at infrared wavelengths of 3.3, 4.7, 12 and 24 microns.

The WISE science survey plan will be developed at UCLA; engineering operations will be conducted at the Jet Propulsion Laboratory's Earth Science Mission Operations Center. Here, science pointing from the survey plan will be integrated with the pointing required for downlink and other engineering activities. Data processing will occur at Caltech's Infrared Processing and Analysis Center (IPAC).

A study of the planning and simulation of space telescope pointing was conducted for a selection of missions already flown, some still in flight. Elements of the mission design, such as the planned observation strategy (all-sky survey vs. single target observations requiring optimized scheduling) and orbit environment, along with the resulting instrument and ADCS subsystem design drive the development of the pointing and the requirements to be verified by simulation. The missions investigated feature a range of mission objectives, observation strategies, instruments, orbits and pointing constraints. For each mission, the combination of these parameters has resulted in a unique design for the process and software used to plan and validate planned spacecraft pointing. Because pointing simulation is often required during both the processes of science planning and command sequencing and validation, both aspects of operations were examined.

2. PLANNING AND SIMULATION OF POINTING BY OTHER SPACE MISSIONS

Infrared Astronomical Satellite (IRAS)^{1,2}

	Dates	Agency	Orbit
	01/83-11/83	NASA, NE, UK	900 km, 99° inclination, sun-synchronous, 6AM ascending node orbit
Mission Objectives	Conduct a survey of the sky in 4 IR bands		
Instrument Description	Ritchey-Chretien telescope mounted inside a superfluid He tank and cooled to 2-5K; detectors at 12, 25, 60 and 100 μm ; passively cooled sunshade		
Pointing Constraints	Point no further from sun than 120° (for solar panel illumination and fine sun sensor range)		
	Point telescope no closer than 60° toward the sun (no sun into telescope aperture)		
	No earth IR inside sunshield or on top telescope baffle		
	Point no closer than 1° toward Jupiter, Mars and Saturn		

IRAS's infrared survey was conducted from a near zenith-pointing attitude. The celestial sphere was scanned with longitudinal swaths $\frac{1}{2}^\circ$ wide. Additional pointed observations were conducted for both instrument calibrations and science data. Science pointing was halted during the approximately two times each day when IRAS passed its ground station in Chilton, UK; at these times engineering operations could be conducted.

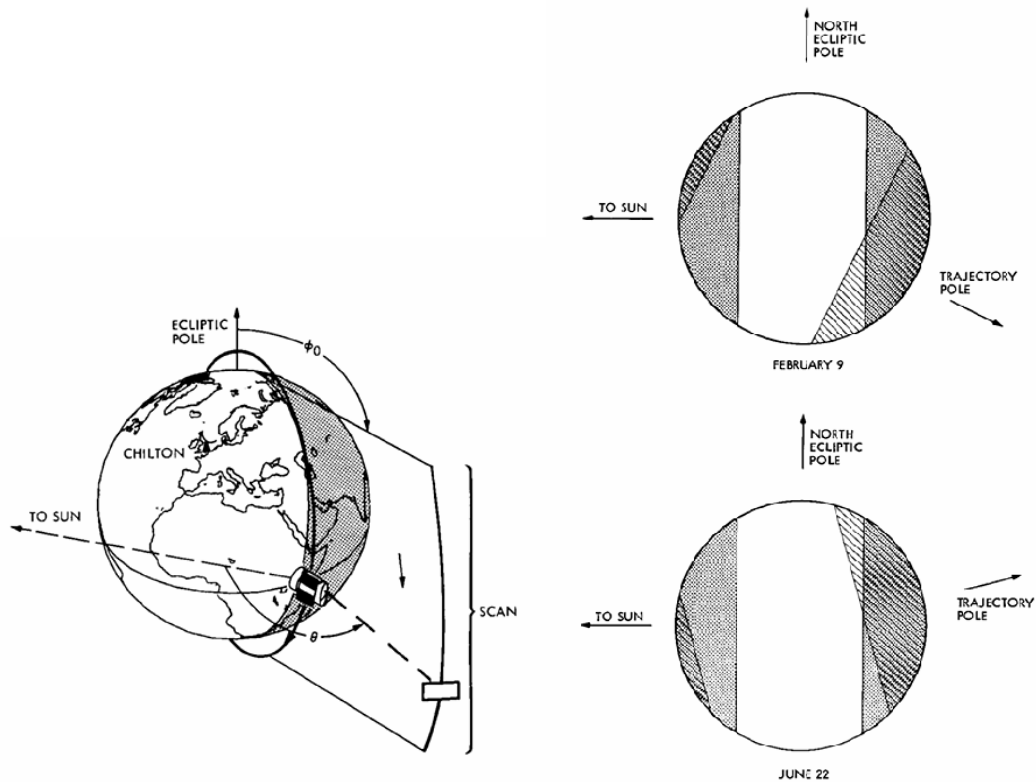


Figure 1. IRAS's orbit and keep-out zones (from Reference 1)

IRAS's constraints (Figure 1) were driven by the need to preserve its cryogen by minimization of orbital heating, as well as to protect the detectors from stray light and saturating levels of flux. In addition, IRAS, like all solar-powered spacecraft, had a requirement to keep solar panels tilted enough toward the sun to provide sufficient power.

Survey observations for a particular week were generated by the Generation Aid for the Survey program. Observations were generated once per week two weeks before planned execution so that the IRAS orbit prediction required as input to the software would be sufficiently recent to predict pointing accurately. The need for an up-to-date spacecraft ephemeris to provide accurate pointing predictions often constrains a final pointing plan and simulation to be within some limited time period before onboard execution of pointing.

Non-survey observations were stored in a database for future scheduling by a separate software program (the Generation Aid for the Non-Survey). Each non-survey observation was associated with a constraint-free window during which it could be scheduled. Both the survey and non-survey observation generation programs checked all planned pointing for constraint violation by modeling the geometry of the pointing; that is, the requested pointing vector was checked to ensure that it did not enter exclusion zones associated with the predicted positions of Sun, Earth and Moon relative to the spacecraft at the planned observation times. The survey was halted during time periods when objects to be avoided (such as the Moon and Jupiter) were predicted to cross the planned line of sight.

Observation scheduling software (the Resident Astronomer's ETL Generation Package) next scheduled observations from the planned survey into a high-level sequence; any available gaps in this sequence were filled with non-survey observations based on their priority and on the minimization of an estimated slew time between observations. The resulting time-tagged, constraint-free list of targets was translated into a sequence of pointing commands that were integrated with the overall spacecraft command sequence.

If a loss in observing time occurred due to a spacecraft problem, an additional software program (SURE) was designed to allow constraint-free re-scheduling of a survey scan given the regions where coverage was lost and the orbits available to reschedule that coverage; typically two orbits per day were reserved (actually, filled with lower priority pointed observations that could be cancelled) for these recovery scans.

Hubble^{3,4,5,6}

	Dates	Agency	Orbit
	4/90-present	NASA, ESA	614 km, 28.5° earth orbit
Mission Objectives	To provide a long-term space-based observatory at near-visible wavelengths		
Instrument Description	2.4m Ritchey-Chretien telescope with currently operating: Advanced Camera for Surveys (1150-11000 angstroms); Near Infrared Camera and Multi Object Spectrometer; Wide Field Planetary Camera 2 (1150-11000 angstroms) and Fine Guidance Sensors		
Pointing Constraints	The instrument must point between 60° and 180° from the sun		
	The instrument must point more than 20° from the illuminated earth		
	The instrument must point more than 6° from the dark Earth limb		
	The instrument must point more than 9.5° from the moon		
Pointing Requirements	Absolute pointing knowledge of .01"; relative pointing stability of 0.007" rms		

Hubble conducts pointed observations for the international community of astronomers via a proposal review process. Once defined by the prospective observers, observations are reviewed by committee, added to an observation database and scheduled based on assigned priority and maximization of observation schedule efficiency. Hubble downlinks science data through a gimbaled high gain antenna via scheduled time on the TDRSS constellation of relay satellites.

As an earth-orbiter, Hubble's constraints are similar to IRAS's; though there is no onboard cryogen to protect, power constraints, orbital heating, stray light and detector saturation dictate attitude keep-out zones. In addition, Hubble's current mode of using its magnetometer (which provides only coarse pointing) and star trackers (which need be protected from Earth occultation) in conjunction with only two gyros to conduct science slews has led to a narrowing of the available viewing regions from its previous three-gyro mode of control.

The point-and-slew mode of observation for Hubble requires that observations be sequenced in a densely packed schedule to maximize science return. This means that the duration of slews between targets, as well as the time required to settle on a target must be accurately accounted for when creating the observation schedule.

Long range schedules of constraint-free observations are generated by scheduling software (SPIKE). Detailed modeling of slews and pointing for a week's observations is conducted by an additional software package which verifies constraints once more (SPSS). Scheduling is done in orbit relative time so that ephemeris updates shift the entire schedule; a final correspondence between absolute time and orbit-relative pointing is conducted a few days before execution.

Infrared Space Observatory (ISO)^{7,8,9,10}

Dates	Agency	Orbit
11/95-5/98	ESA	5° inclination earth orbit, perigee at 1000 km, apogee at 70600 km, 24 hour period

Mission Objectives	To perform scientific observations of a variety of near and distant objects in the infrared
Instrument Description	60 cm Ritchey Chretien cassegrain telescope, with detectors ISOCAM (camera at 2.5-17 μm), ISOPHOT (photo-polarimeter at 2.5-240 μm), LWS and SWS (spectrometers at 43-197 and 2-45 μm , respectively) in a 1.8K superfluid helium dewar protected by a sunshade
Pointing Constraints	Point no further from sun than 120° (for solar panel illumination)
	Point telescope at least 60° away from the sun (protect telescope from sunlight/solar heating)
	Point no closer than 77° to the Earth limb
	Point no closer than 24° to the Moon
	Point no closer than 7° toward Jupiter
Pointing Requirements	Jitter (relative pointing error) < 2.7", absolute pointing drift < 2.8", absolute pointing error < 11.7"

ISO performs pointed observations in the infrared. Like Hubble, these observations are selected by scientific priority and arranged to most efficiently utilize available observing time.

ISO's elliptical orbit precluded data taking near perigee, where radiation from the Van Allen belts created problems for detectors. Constraints for the high altitude portion of the orbit were similar to those of IRAS and Hubble, and ground simulation of pointing again needed to optimize scheduling as well as verify allowable pointing.

Constraints were checked, first, via geometric modeling of proposed pointing vectors in proposal handling software; next, slews were modeled with mission planning software used to create the planned observation schedule; finally, pointing commands developed from this schedule were validated on a high-fidelity flight simulator prior to uplink. One problem experienced by ISO, which served as a lesson learned for Spitzer, was that the various software programs used to estimate turn durations often yielded conflicting results; this led to a design for Spitzer in which a single pointing simulation program (discussed below) was called by the applications used through the process of mission planning, sequencing and sequence validation.

X-Ray Multi-Mirror Newton (XMM Newton)^{11,12}

	Dates	Agency	Orbit
	12/99-present	ESA	40° inclination earth orbit; perigee at 7000 km, apogee at 114000 km; 48-hour orbital period
Mission Objectives	To conduct extended observations of x-ray sources, including medium-resolution spectroscopy at .35-2.5 keV and broad-band imaging spectroscopy from .1-15 keV		
Instrument Description	3 80 cm x-ray telescopes; 3 European Photon Imaging Cameras; 2 Reflection Grating Spectrometers; 1 30-cm Optical Monitor telescope; spectrum covered is 12 keV-0.1keV		
Pointing Constraints	Point no further from sun than 110° (for panel illumination)		
	Point telescope more than 70° from sun (prevent sunlight from entering telescope)		
	Point more than 47° from Earth limb		
	Point more than 22° from the Moon		
	Additional constraints for the planets to protect the instrument from bright sources.		
Pointing Requirements	RPE < 1.3'', absolute measurement accuracy < 6.2'', APE < 9.5''		

XMM conducts pointed observations at x-ray sources, also from an elliptical earth orbit like ISO. Besides verifying constraints and estimating turn and settling times, XMM had the additional requirement that the ground simulate pointing sufficiently to plan gyroless slewing. Like Hubble, limited gyro use (in particular, restricted to eclipses) is

required to increase gyro longevity over the possible 10-year mission; in XMM's case, this means that all four of XMM's gyros are turned off during science operations in orbit day. Slews larger than the star tracker field of view use open loop control on one axis and fine sun-sensor directed closed loop control on the other two axes; fine pointing in all three axes is implemented at the end of such a slew by the star tracker. For the ground system, this means a more high fidelity pointing simulation is needed.

For mission planning, a database of observable bins around the sky, often 2° by 2°, is defined by assigning each bin a constraint-free time of visibility; only targets which fall into a completely visible bin are considered for scheduling at a given time. Next, selection of a candidate list of targets is done using a non-automated, iterative process using geometric plots and the human eye to design sequences of target pointing that do not violate constraints and minimize slew time; finally, once a list of targets has been produced, it is forwarded to a flight dynamics operations group for more detailed modeling of slews and constraint checking. Reaction wheel speeds are also predicted based on planned turns and the simulation of environmental torques such as solar pressure and gravity gradient. This verifies that wheel speeds will not become saturated during a slew to an observation.

Even with the extensive dynamic pointing simulations performed for XMM, guide star acquisition following an open loop slew may not succeed; hence a software system was designed to provide on-call support to non-expert flight controllers. The software allows the controller to perform attitude determination and any attitude correction maneuvers required at the end of a slew. Telemetry input into the software allows calculation of the time for which the current attitude is constraint-free; it also allows attitude determination with star field pattern matching using the star tracker's observed field. The software then provides the flight controller with parameters for a final safe slew back to the intended position.

Galex^{13, 14, 15}

	Dates	Agency	Orbit
	4/03-present	NASA	690 km, 29° inclination earth orbit with a 99 minute period
Mission Objectives	Five imaging surveys will be carried out in the FUV (.135-.175 μm) and NUV (.175-.275 μm); three spectroscopic surveys will be done at .135-.275 μm		
Instrument Description	50 cm Ritchey-Chretien telescope with FUV and NUV detectors		
Pointing Constraints	Telescope assembly boresight must point at least 20° from sun center throughout the orbit, and 85° from sun center on the eclipse side of orbit		
	Spacecraft operations shall avoid pointing the boresight closer than 88° to the center of the sun		
	Spacecraft operations shall avoid pointing the boresight closer than 30° from Earth limb		
	Spacecraft operations shall avoid pointing the boresight closer than 40° from lunar limb		
	Science operations shall avoid pointing the boresight closer than 40° to the RAM vector		
	Additional object avoidance constraints (galactic plane, ecliptic plane) to reduce detector background/fatigue and star tracker exclusion zones		

On Galex (Figure 2), science data is taken only during orbit night; detector voltages are ramped up at entrance into eclipse, the telescope is pointed at planned survey or observation locations, and then detector voltages are ramped down again before entrance into orbit day. Mission planning software at the Galex Science Operations Center generates an efficient, constraint-free time tagged sequence of pointing and instrument commands each week; this is passed to the Mission Operations Center for integration with engineering activities and uplink.

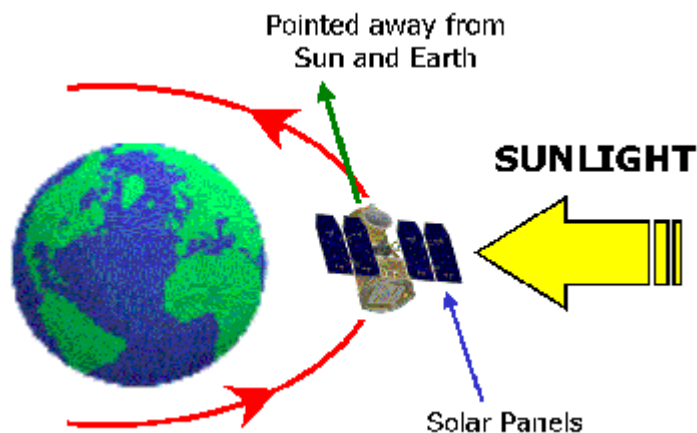


Figure 2. Galex nominal orientation (from <http://www.galex.caltech.edu>)

Pointing constraint violations are of particular concern as Galex enters and exits eclipse, when the detector voltages are ramped up and down, respectively; these large slews to and from science attitudes (as well as the smaller slews between observations) are typically simulated by two different ground software programs. For Galex, slew profiles are not commanded but determined onboard, making them somewhat unpredictable. Science planning operations software translates desired observations into pointing commands and approximates expected slew profiles to verify constraints are followed. Several iterations on the planned pointing directions are usually required to meet constraints. In addition, a second, independent simulation is performed at the mission operations and control center once a validated sequence of pointing is passed from science operations. Typically, this modeling is done with a geometric modeling software package, but is occasionally done with a complete closed-loop attitude control simulator which included sensor stimulations, flight-like electronics and modeling of environmental torques.

For Galex, no regular modeling of reaction wheel speeds is required for planning wheel desaturation; because science data is only taken on the eclipse side of orbit, magnetic torquer bars are enabled during orbit day.

Spitzer^{16,17,18,19}

	Dates	Agency	Orbit
	08/03-present	NASA	Earth-trailing 1 AU heliocentric orbit drifting from Earth at .12 AU/year
Mission Objectives	To perform scientific observations of a variety of objects in the infrared, including brown dwarfs, early galaxies and protoplanetary debris disks		
Instrument Description	85 cm telescope with 3 instruments kept at 5.6K by a superfluid He cryostat; Infrared Array Camera (images at 3.6, 4.5, 5.8 and 8.0 μ m; Infrared Spectrograph (spectroscopy at 5-38 μ m); Multiband Imaging Photometer (photometry and imaging at 24, 70 and 160 μ m)		
Pointing Constraints	The angle between the boresight and the sun may never exceed 120°		
	The angle between the boresight and the sun may never be less than 82.5°		
Pointing Requirements	Pointing Stability < 0.1"; Pointing Accuracy (to command) < 0.5"		

Spitzer's Earth-trailing orbit allows its pointing to be less constrained, as evidenced by the two hard pointing constraints listed above (illustrated in Figure 3). Like the other point-and-slew missions, observations are sequenced in a densely packed schedule to maximize science return. In addition, Spitzer's science pointing must be integrated with turns required for communications to the Deep Space Network via a fixed high gain antenna (conducted about 2X/day).

Astronomical Observing Requests (AORs) are built using a software tool which provides an estimate of the duration of observations (SPOT). AORs are loaded into a science operations database; another software tool (AIRE) expands the observation parameters into instrument and S/C commands. A pointing control subsystem model called by AIRE

provides a more accurate estimate of the attitudes throughout and duration of an observation (including settling time). Settling times are estimated by a simple table look-up model.

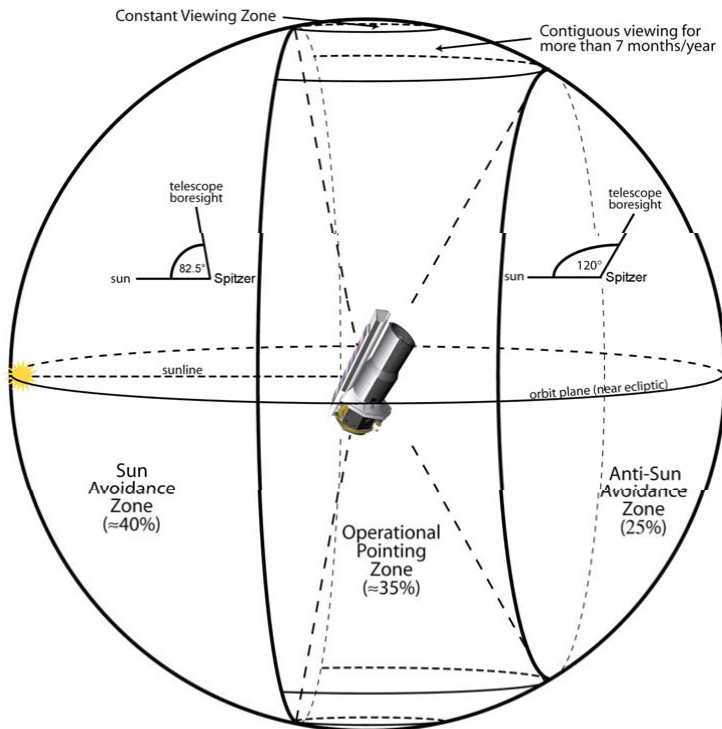


Figure 3. Spitzer's allowable viewing zone (from Reference 20)

While the duration of slews between targets, as well as the time required to settle on a target without excessive jitter, must be estimated to create the observation schedule, Spitzer's flight software can override the scheduled timing based on the values of flight software variables. This makes Spitzer less sensitive to error in the estimates of slew and settle duration by the ground simulation.

Planning and scheduling software (SIRPASS) arranges observations into an efficient schedule (minimizing slew times between targets). The pointing simulator used by AIRE is now used to determine slew profiles between observations and better estimate observation attitudes and duration. Expected turn profiles are modeled using the algorithms of the attitude control flight software; disturbance torques are not captured because it is assumed they are minimal at Spitzer's orbit.

The final integrated command sequence, which includes not only science observations but instrument calibrations and turns to Earth for DSN data transmissions, is also run through the same pointing simulator. Attitude constraints are captured in all pointing simulation.

Cassini^{20,21}

	Dates	Agency	Orbit
	10/97-present	NASA, ESA, ASI	Saturn
Mission Objectives	Science data from the Saturn system		
Instrument Description	(Optical remote sensing): Composite Infrared Spectrometer (7-1000 μ m), Imaging Science Subsystem (200-1100nm), Ultraviolet Imaging Spectrograph (55.8-190nm), Visible and Infrared Mapping Spectrometer		

	(0.35-1.07 μ m)
Pointing Constraints Include:	VIMS (-Y) Sun Viewing Constraints
	UVIS (-Y) Sun Viewing Constraint
	CIRS Cooler Solar Viewing Constraints when +X to Sun < 88.6 deg
	CIRS Cooler Solar Viewing Constraints when +X to Sun < 85.5 deg
	[Many additional constraints...]

While Cassini is not exactly a space telescope, it provides perspective on the complex pointing plan required by a large suite of instruments (in this case, 12; see Figure 4 for body axes used for pointing). Science observations are usually conducted in parallel, with a prime instrument orienting a primary spacecraft axis and allowing a second “ride along” instrument to fix the pointing by orienting a secondary spacecraft axis.

Body Vectors

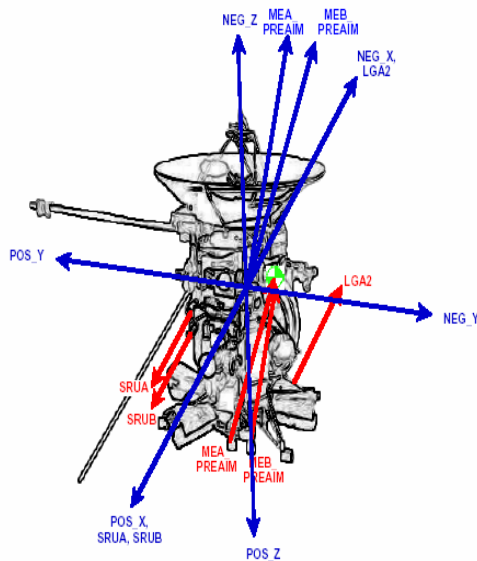


Figure 4. Cassini’s body-fixed axes used for pointing (*from Reference 21*)

Cassini has several ground software tools to generate and model spacecraft pointing. The Science Opportunity Analyzer tool analyzes the geometry of observations based upon the predicted positions of the spacecraft and possible targets during a particular time period (and thus takes as input various required ephemerides). The geometry of attitude constraints can also be modeled.

The main tool used to plan detailed turns and tracking for science observations and engineering activity pointing is the Pointing Design Tool (PDT). This tool is used by instrument teams to design individual observations during an instrument’s allotted time period; it is also used to design the way points between each instrument’s block of time (way points are locations at which the spacecraft is “reset” to a predefined attitude), to plan downlink periods and to design optical navigation pointing. It takes as its input ephemeris data for objects of interest (the spacecraft, targets, the Earth, etc.) and generates pointing commands which direct body-fixed vectors to the planned targets with the assistance of an additional program (IVP). It also models the turning of the spacecraft specified by these commands by calling upon a separate tool which is used again later to validate the final sequence of pointing before uplink.

This latter tool, called the Kinematic Predictor Tool (KPT), propagates the motions of the spacecraft based on pointing commands. In this mode, the attitude control flight software is emulated to determine pointing profiles for turns and tracking. KPT also models reaction wheel speeds via a dynamic modeling mode in which the transfer of wheel torques

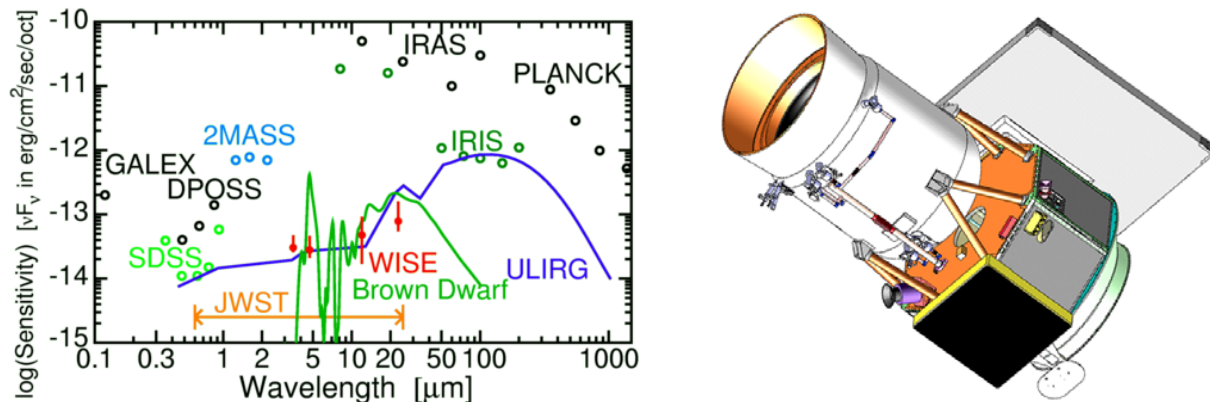
to the spacecraft, including wheel friction, is captured. Interaction between the reaction control system (RCS) of thrusters used for momentum unloading and the reaction wheels is simulated, including the RCS deadband control logic. Dynamic constraints on Cassini's attitude, such as reaction wheel and RCS torque authority, are checked and flagged if violated. All calculations are performed at several hundred times real time.

Particularly because Cassini's complex pointing design process takes a long time, sufficient margin is added to all planned turn times to allow for a location different than that predicted in the ephemeris used at the time the pointing was designed. The largest difficulty with Cassini's pointing process and software has been the time consuming nature of designing pointing for one instrument that doesn't violate the attitude constraints of another. Usually, the shortest turn to a desired attitude is not one that is constraint-free; and Cassini did not have available a simple, fast pointing simulator to coarsely design allowable turns for mission planning purposes.

3. PLANNING AND SIMULATION OF POINTING FOR WISE^{22,23,24}

3.1. The WISE Mission

WISE is a NASA-funded, earth-orbiting spacecraft set to launch in June 2009 for a 7-month primary, 13-month extended mission. The planned orbit is a 97.3° inclination dawn/dusk sun-synchronous orbit with a PM ascending node. The single instrument on WISE is an infrared telescope which will be cooled by means of a cryostat filled with solid hydrogen. The purpose of the mission is to conduct an all-sky survey at four infrared wavelengths. Figure 5a plots the observed wavelengths versus sensitivity of WISE as compared with several other surveys. Figure 5b depicts the spacecraft, the bus of which is being developed by Ball Aerospace; the instrument is being developed by Space Dynamics Laboratory.



Figures 5a and 5b. (5a) WISE 5 sigma point source sensitivities versus that of other surveys; (5b) the WISE spacecraft; on the bus (lower right), the flat plate high gain antenna is in the foreground and the solar panel in the background. The cryostat (upper left) contains a 40-cm telescope and two detectors. It is topped by a conical shade.

3.2. WISE Pointing

3.2.1. Spacecraft Orientation

The spacecraft is oriented so that the +Y-axis of the spacecraft, where the solar panel is mounted, is pointed toward the sun; the +Z-axis, approximately along the instrument boresight, is normal to the Sun line (which is in the ecliptic plane); and the +X axis is parallel to the velocity vector.

3.2.2. Science Pointing

The survey plan requires the telescope to scan a semicircle about the sky each half orbit that is near normal to the sun line at a constant orbital rate. While the telescope is scanning this semicircle at approximately orbit rate, a single-axis motorized scan mirror freezes each image for about 9 seconds of an 11-second scan cycle. Scans start and end near the ecliptic poles. The amount by which the telescope line of sight is off the normal vector to the sun will be specified by several survey plan input parameters. These parameters provide compensation for the South Atlantic Anomaly (by means of an alternating toggle in the pointing), for moon interference (by avoiding the moon by placing scans ahead or behind it as it crosses the line of sight) and for unplanned outages (by looking ahead of the sun when possible to preemptively fill-in potential coverage gaps).

3.2.3. Communications Pointing

The spacecraft communicates via the TDRSS constellation. Because the high gain antenna is fixed on the –Y side, the spacecraft will need to be turned to point the antenna toward the geostationary TDRSS. Contacts will occur during polar passes, which receive maximum science coverage, to minimize the impact on science data collection.

Contacts will occur on the dark side of the Earth; typically there will be a 4 hour period when TDRSS East will be in unconstrained view followed 4 hours later by a 4 hour period when TDRSS West will be in unconstrained view. Approximately 4-5 TDRSS passes will be scheduled each day to downlink the day's worth (25 gigabytes) of science data.

3.2.4. ADCS Design

WISE is a three-axis stabilized spacecraft with one Ball star tracker, an inertial measurement unit with three gyros and accelerometers, a three-axis magnetometer, fourteen coarse sun sensors, three off-axis orthogonal reaction wheels and torque rods. There is no propulsion system.

3.2.5. Pointing Constraints

Both the sun and earth must be prevented from shining into the instrument aperture at all times to avoid excessive heat loads into the cryo-system, which would result in significantly reduced mission lifetime. The following pointing constraints apply:

1. The sun shall never be allowed to shine into the flight system aperture shade. The dot product $\text{SHADE} \cdot \text{SUN}$ shall always be less than $\sin R_{\odot}$. Here, $\text{SHADE} = (0, -\sin 8^{\circ}, \cos 8^{\circ})$ in the above-mentioned body coordinates and is the normal to the cone of the telescope sunshade; SUN is the unit vector pointing to the sun; and $R_{\odot} = 0.25^{\circ}$ is the angular radius of the sun.
2. The earth shall not be allowed to shine into the flight system aperture shade. The earth avoidance angle shall be within 32 degrees off zenith in roll and pitch.
3. The solar panels must be illuminated to provide power. Thus the y-component of the SUN vector must be greater than $\cos(15^{\circ})$ during normal science operations.

3.2.6. Pointing Requirements

WISE must meet the following pointing requirements:

- Pointing Accuracy: During science operations, the bus shall provide inertial pointing accuracy of 75 arcsec (per axis, 1-sigma); In all operational modes, the bus shall provide attitude rate knowledge to less than 0.063 degrees per second (per axis, 1-sigma)
- Attitude Knowledge: In all operational modes, the bus shall provide inertial attitude knowledge to less than 60 arcsec (per axis, 1-sigma); in all operational modes, the bus shall provide attitude rate knowledge to less than 0.063 degrees per second (per axis, 1-sigma)
- Jitter: The ADCS shall provide pointing stability performance less than 0.6/5.0/0.9 arcsec (R/P/Y) over 8.8 seconds (1 sigma, per axis) during operational [science data-taking] mode.

3.3. WISE's Pointing Operations Process

An initial survey plan will be constructed by the WISE science planning team, led by Ned Wright at UCLA. This plan will contain pointing for scans over the entire mission. It is expected that updates to this original plan will be received during the course of operations if data is lost and sky coverage needs to be regained; or if a new plan is desired based on

updated information about WISE's orbit or performance. These science plan updates can be sent to engineering operations at JPL up to a few weeks before their planned execution. Once an updated science plan is received at JPL, it is integrated with TDRSS pointing. The final command sequence of pointing planned for uplink is run through a pointing simulation program to verify no constraints are violated. Momentum management is not conducted on the ground because WISE, like Gallex, plans to enable the flight software to desaturate wheels periodically at polar passes.

3.4. WISE's Ground Software for Pointing Operations

Two software programs will be used to plan, integrate and simulate WISE pointing. The first, to be used at the WISE Science Planning Center, is the Survey Planner software. This software accepts as input the two-line element (TLE) providing orbit information for WISE and the values of several survey parameters. It calculates the projected positions of WISE, the moon and sun and produces as output a set of scan quaternions and rates. In doing so, it validates that the plan satisfies WISE's sky coverage requirements (4 or more independent exposures in each filter at each sky position over at least 95% of the sky).

A second software package is used to plan TDRSS pointing, integrate it with the science pointing and simulate all pointing in the final command load. This program, called PGEN, will take as input the science plan, a file containing the planned TDRSS pass schedule (where constraint-free views to TDRSS are determined by an independent program developed by WISE navigators) and the WISE and TDRS ephemerides (also projected from TLEs by independent navigational software). PGEN will insert pointing for TDRSS passes into the science pointing schedule during the times specified in the TDRSS pass schedule and return to the science pointing plan after the end of each TDRSS pass. It will output a time-tagged set of pointing commands corresponding to this integrated pointing plan.

Once these pointing commands have been integrated into the overall command sequence, PGEN will accept as input the output of the sequence generation software in the form of a listing of all time-ordered commands. Given a command to turn from the input command sequence, PGEN shall generate a profile for that turn (S/C rotational speed vs. time) that agrees with that produced by the ADCS flight software for the same command. PGEN shall simulate the rotation of the S/C body axes through the projected profile for each turn. PGEN shall model S/C attitude for science pointing or between turns based on the specified end quaternion and rate. At each time interval in its simulation mode, PGEN shall verify that S/C pointing satisfies all pointing requirements. PGEN will output a log of all keep-out zone violations found in simulation mode.

4. CONCLUSION

While the ground system software and corresponding operational processes used to generate and validate pointing for the missions examined herein are all different, the major difference is the obvious one, namely whether the mission features a survey or scheduled observations. Much has been written about the optimization of scheduled pointing. Besides this fundamental difference, all of these missions require modeling of instrument pointing by ground software. These simulations can be elaborate, but often a simple kinematic model suffices. Such a simple model was selected for WISE based on the simplicity of the survey plan and operations.

5. ACKNOWLEDGEMENTS

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